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About LNG energy utilization efficiency estimation

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Abstract

The amount of LNG demand is continuously increasing now. The main disadvantage of the LNG in comparison with traditional NG transportation is a fact that to liquefy LNG it is necessary to spend energy and then add some heat to re-gasify it. Regasification process is usually carried out with loss of the low-temperature potential, which is created during LNG liquefaction. This potential can be utilized for energy generation, and the realization of potential utilization may be executed in several ways: by heat rejection from thermodynamic cycle and thus increasing its efficiency, preliminary pressurizing of LNG by pump or thermal compression and its further expansion in turbines or combinations of these two methods. This article deals with the estimation of maximal work which can be obtained from re-gasification of 1 kg of LNG by these methods. The calculations show that most efficient methods are heat rejection and thermal compression.

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Keywords: cold energy, liquid natural gas, regasification, exergy

1. Introduction

The idea of cryogenic fluids cold energy utilization gains worldwide acceptance in recent time [1-3]. It is mainly caused by increasing volumes of LNG production, common trend of energy saving and energy potential stored in cryogenic fluids as the energy consumed during liquefaction.

During usual LNG re-gasification (which is most cases utilize a heat from the environment or waste heat) working fluid lost its low-temperature potential when its temperature reach the value of the environment. If pressures are also equal, potential energy of compressed gas is also lost.

The main ways of LNG energy potential utilizing are:

- Use of the cryogenic working fluid as a low heat source in direct cycle converters for rejection of the heat Q_2.

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- Application of the thermal compression during LNG re-gasification with further utilizing of high-pressure gas in expansion machines with electric energy generation.
- Combined schemes including first and second cases.

In all cases it is considered that LNG after re-gasification is directed to a consumer in gaseous state with given parameters of pressure and temperature.

During the selection of LNG energy potential method selection and development of the plant for additional energy generation, the matter of thermodynamic efficiency and comparative assessment of such energy plant as well as of limited possibilities of LNG as low heat source and as working fluid became actual.

2. Regasification with cryogenic working fluid cold energy utilizing in a Carnot cycle

Let`s consider a hypothetical energy plant (Fig. 1) which executes a direct Carnot cycle, which is carried out in temperature limits of cryogenic working fluid (lower source) and environment (high source).

Considering that temperature head between working fluid and heat source is equal to zero, on 1-4 branch only heat from the phase change is used, on 4-5 branch physical heat of the gas with changing temperature T_{ci} is utilized in every elemental Carnot cycle.

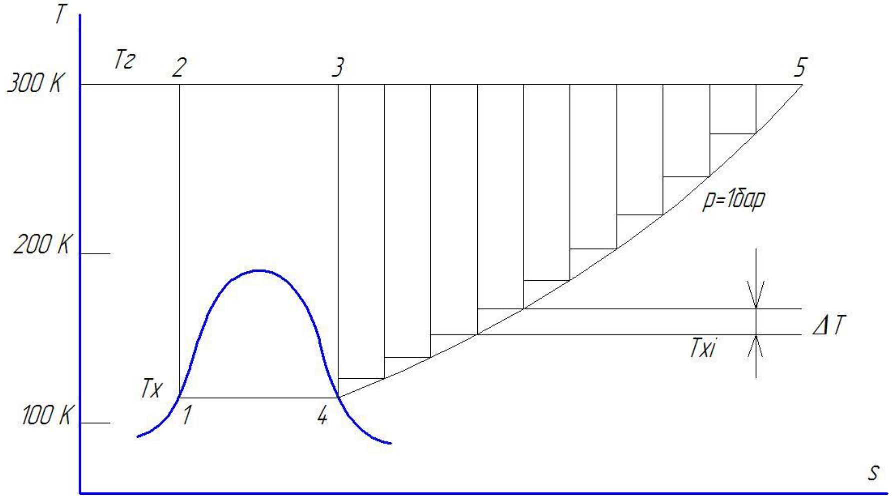

Fig. 1. About calculation of maximal work generated in the cycle during cycle heat rejection to cryogenic fluid.

With provided assumptions the work in the 1-2-3-4 cycle for 1 kg of LNG can be determined as:

$$L = Q_1 - Q_2.$$

Rejected heat Q_2 per 1 kg of LNG will be fixed value for given parameters of cryogenic fluid $Q_2 = m \cdot r = 1 \cdot 510 = 510$ kJ/kg.

Considering, that for Carnot cycle: $\eta_{Carnot} = 1 - T_c / T_h = 1 - Q_2 / Q_1$ where Q_1 – added heat:

$Q_1 = Q_2 \cdot T_h / T_c$.

Then the work of the cycle will be equal to:

$$L = Q_2 \left(T_h / T_c - 1 \right).$$

On branch 4-5 work for every elemental Carnot cycle will be determined by similar relation:

$$dL_i = dQ_1 - dQ_2 = dQ_2\left(T_h / T_{ci} - 1\right).$$

Available heat (cold energy of cryogenic fluid) rejected from elemental cycle is calculated as:

$$dQ_2 = m_{LNG} c_{pci} dT_{ci}.$$

The work of 4-3-5-4 cycle can be calculated as the sum of the elemental Carnot cycles works but in extreme cases it will correspond to work of this cycle with heat adding in isothermal process 3-5 and heat rejection in isobaric process 5-4.

The calculation results show that theoretical work of the 1-2-5-4-1 cycle per 1 kg of LNG is equal to 1093-1146 kJ. If other heat source (instead of environment) is used, cycle work and thermal COP will change correspondingly (Fig. 2).

Thus, received theoretical characteristics show that any energy system suited for electricity generation and utilizing LNG cold energy cannot produce more work or has a higher COP then the values described above.

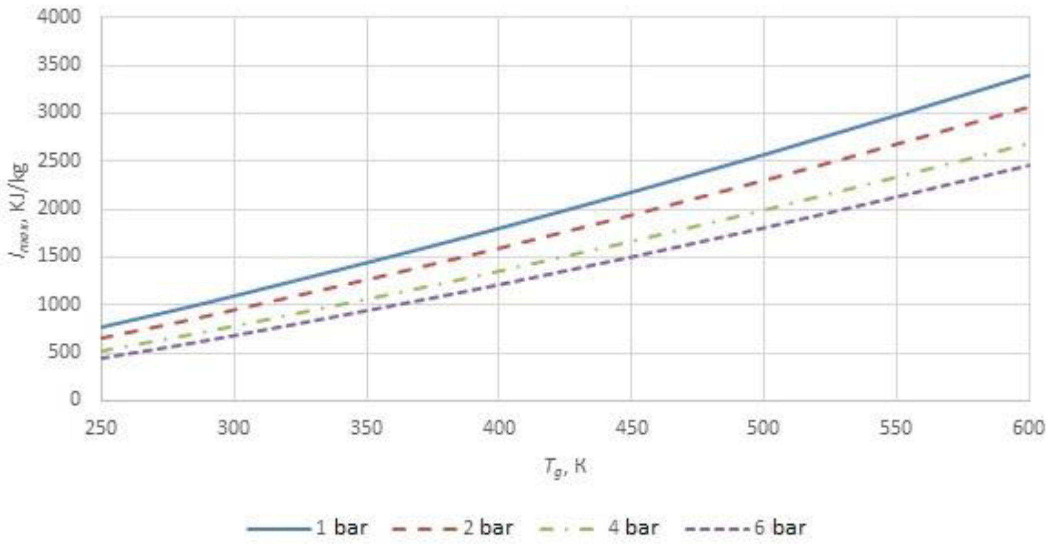

Fig. 2. Dependency of the maximal specific work generated by 1-2-5-4-1 cycle with cycle heat rejection in to cryogenic fluid from heat source temperature and LNG pressure.

3. Re-gasification with preliminary pressure rising

Additional work during re-gasification process can be produced not only by utilizing of cryogenic fluid cold energy as a heat sink but also by work produced by cryogenic fluid itself. For this purpose it is necessary to rise its pressure. In case of cryogenic fluid there are two principal methods of pressure rising: increasing of the pressure in pumps when the cryogenic working fluid is in liquid state and thermal compression. Generation of the electric energy in such plants is executed in expansion turbines.

Thermodynamic analysis of such plants shows that work producing is provided by realization of open Rankine cycle. Indeed, process of gasification with cryogenic fluid pumping consists of next processes (see Fig. 3): pumping of cryogenic fluid into gasifier (process 1-2), where evaporation and vapor overheating takes place (processes 2-3 and 3-4).

Work spent on the pump drive is often not taken into account during preliminary calculations due to its almost negligible value in comparison with the values of generated work or added heat. Then expansion on turbines with energy generation takes place (process 4-5). Parameters in point 5 depend on expansion ratio. In any case the temperature after expansion became lower than the temperature of the environment and if the pressure of the working fluid is still higher than the pressure of the environment, working fluid can be heated up to a temperature of the hot heat source and then expanded again in the second turbine. It is obvious that multi-stage expansion can be used where the choice of the turbine number is the task of optimization. This task was solved in the [4] where it is shown that in the optimized plant there is a possibility to reach a 90% efficiency of expansion process.

There is a possibility for plant (Fig. 4) cycle work increase. To enlarge produced work it is necessary to increase pressure which is executed by cryogenic pump. If we assume that that there is no limitation of higher pressure value (and they are actually exist [5]), it is possible to notice that cycle work is also significantly increased. But energy consumptions for pump drive are also increased and it is necessary to take them into account in energy balance.

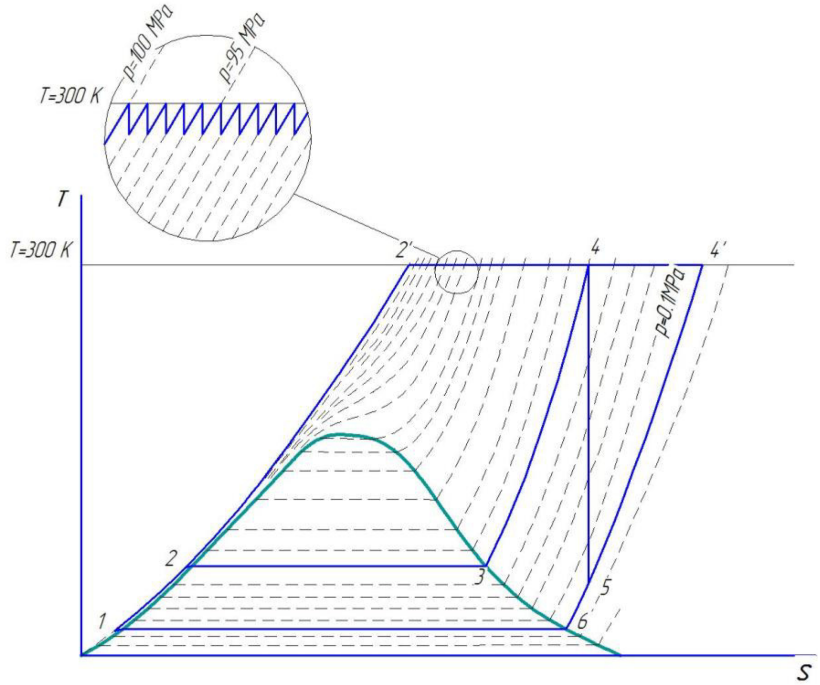

Fig. 3. About calculation of maximal cycle work during cryogenic product pressurizing.

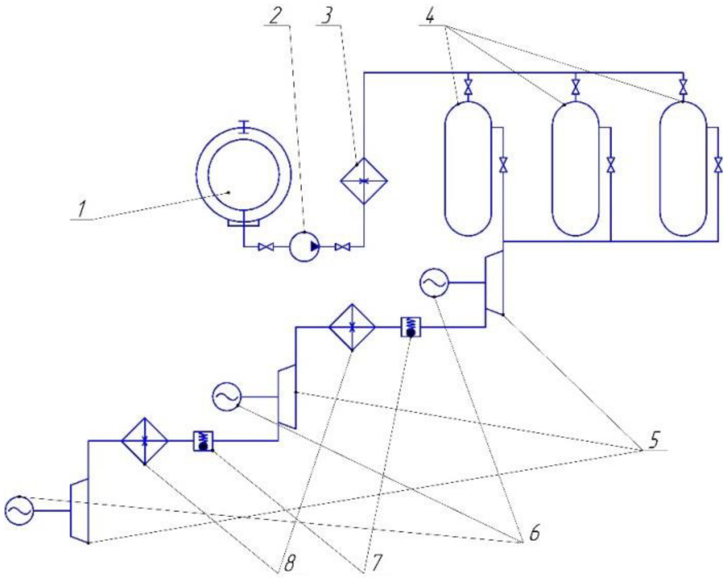

Fig. 4. Scheme of plant for LNG regasification with preliminary cryogenic fluid pressure increase

1 – LNG tank; 2 – pump; 3 – evaporator; 4 – tanks for evaporated cryogenic product storage; 5 – turbines; 6 – electricity generators; 7 – gas reducers; 8 - heaters.

Maximal theoretical work of the cycle is realized by infinite number of turbines with intermediate heating of working fluid which will correspond to isothermal process 2'- 4'. The calculations (Fig.5) show that with asymptotical behavior of the useful work function of pressure and almost linear function of energy required for pump drive, there is a clear maximum with pressure equal to 65 MPa and maximal work equal to 853.3 kJ/kg.

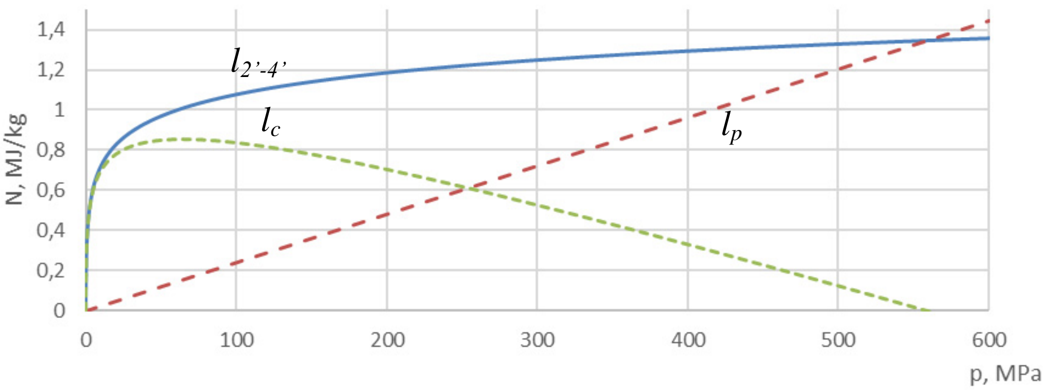

Fig. 5. Cycle work, required pump power and effective power output in cycle on maximal cycle pressure.

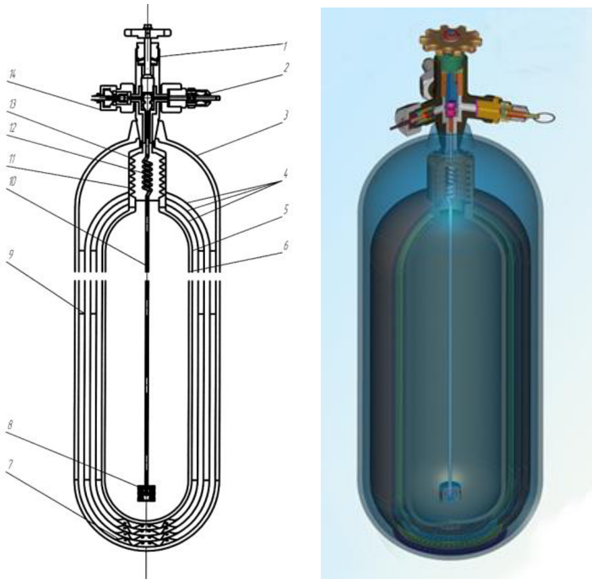

Fig. 6. Design of tank suited for thermal compression

1 – valve; 2 – safety valve; 3 – tank; 4 – screens; 5 – heat insulation; 6 – Dewar vessel; 7 – compressive plate; 8 – filter; 9 – amortizing fitting; 10 – intake tube; 11– bellows; 12 – serpentine; 13 – barrel; 14 – filler connector [7].

Heat, added in process 2-4’, is determined by expression:

$$q_1 = l_{2'-4'} = RT \ln\left(p_{2'} / p_{4'}\right),$$

rejected heat is cold energy of 1 kg of LNG:

$$q_2 = i_{4'} - i_1.$$

Required pump drive power:

$$l_p = i_{2'} - i_1,$$

useful cycle work (without required pump drive power):

$$l_c = l_{2'-4'} - l_p.$$

The calculations for LNG show that during considering optimal cycle pressure (see Fig. 3) and expansion to a pressure of point 4’, useful cycle work will be equal to 850 kJ/kg and higher dependently on temperature of high heat source (Fig. 6).

Let’s consider a thermal compression in closed volume of tank. It can be a natural process of re-gasification by heat fluxes through the walls [6] or in external heat exchanger which is connected only with the tank. Example of such tank is presented in figure 6. In most cases it is more appropriate to use regasification in external heat exchanger [7] because this process is easier to control and time of regasification and gas heating is significantly reduced. In suggested tank re-gasifier mass of cryogenic product, which is filled in inner volume of tank, does not fill the volume of entire tank and is determined from the condition of pressure in the tank final state. If consider the possibility of tank which is capable to tolerate a pressure of gasified cryogenic product which fills the entire volume of tank, it is obvious that this pressure will be maximal.

Mass of the filled liquid is calculated from the volume of liquid which is equal to tank volume:

$$m_l = \rho_l V.$$

For certain liquid (LNG for example) by its density and final temperature we can determine a value of pressure. For LNG this value is equal to 320 MPa.

This value witnesses that by thermal compression it is possible to obtain a pressure higher than optimal in case of mechanical compression. This means that by thermal compression caused by the heat from the environment of waste heat, it is possible to obtain more useful work than in case of mechanical compression by means of isothermal expansion:

$$N_{tc} = RT \ln \frac{p_1}{p_2} = 519.6 \cdot 300 \cdot \ln \frac{320}{0.1} = 1.258 MJ.$$

In the same time, creation of the tank which is capable to resist pressure of 320 MPa is problematical. Even if we consider a possibility of such tanks creation, they will be limited by the level of pressure equal to 50...70 MPa.

These conditions correspond with aforementioned case with cryogenic product pumping. Considering that in case of tank emptying during some time, its pressure became lower as well as generated useful work, system with thermal compression can be less effective than pumping.

Thus, in preliminary study we can consider that maximal values of obtained work and its efficiency are similar for systems with cryogenic product pumping and thermal compression.

4. Combining of cycles with preliminary pressure increase and that rejection to cryogenic product

There is also a possibility to combine aforementioned methods of LNG cold energy use. In such plants heat is rejected from the cycle to cryogenic product which pressure is preliminary increased. In first cases such plants are applied in cycles where application of working fluids with higher saturation temperature is required. The example of the plant which utilizes Rankine cycle with preliminary pressure increase is presented in Fig. 7.

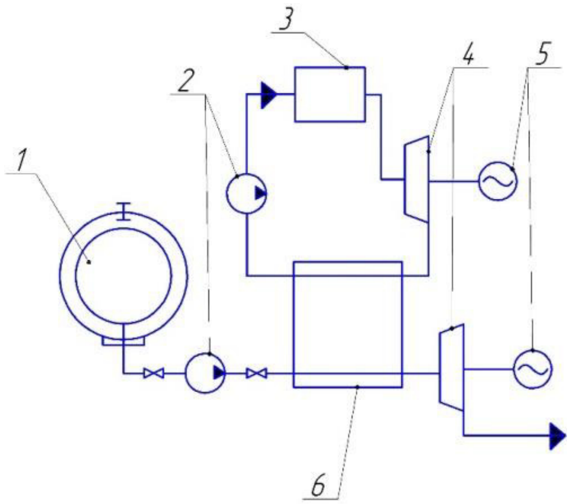

Fig.7. Re-gasification facility with combination of the preliminary pressure increase with heat rejection from Rankine cycle to cryogenic product: 1 – LNG tank; 2 – pumps; 3 – evaporator; 4 – turbines; 5 – electricity generators; 6 – evaporator-condenser.

Total work output of such plant will be summarized from two works: obtained in closed cycle and obtained as the result of cryogenic product expansion. In extreme case work generated in aforementioned case will be summarized from the work of the plant described in chapter 2 and work obtained by cryogenic product expansion:

$$l = l_{2-2'-4-3-2} + l_{4-4'} - l_{1-2} \ ,$$

Processes will correspond to figure 3, where 1-2 – increase of the cryogenic product pressure by pump, 4 – 4' – isothermal expansion of the re-gasified cryogenic product; 2-2'-4-3-2 – cycle described in chapter 2. Expressions for the cycle calculation are presented above.

For example, in case of preliminary pressure increase to 0.6 MPa, maximal work which can be obtained by heat rejection from the cycle to cryogenic product will be equal to 676.1 kJ/kg (Fig.2).

Isothermal expansion work from the 0.6 to 0.1 MPa with temperature 300 K is equal to 279.3 kJ/kg, work for pump drive – 1.1 kJ/kg. Thus, total work obtained in such cycle with taking power for pump drive into account is equal to 954.3 kJ/kg. It allows to make a conclusion that by means of thermodynamic combined method is less effective than heat rejection of pressurizing. However, it may be taken in consideration during designing of the plant with working fluids which have a relatively high saturation temperature.

5. Cryogenic product use efficiency criteria

The results of the presented research are the recommendation for efficiency estimation of the energy plant and system suited for energy generation during the cryogenic product regasification. The most simple and physically understandable criterion is the relation of produced work per mass unit of cryogenic product:

$$l_{sp} = \frac{N}{G}\frac{kJ}{kg}.$$

where N is plant power output, G is cryogenic product flow rate.

Given criterion can be used for comparison of the plant which work in the same temperature level. The second criterion is the efficiency of energy generation during regasification dependently on type of the heat source (or temperature of the heat source), which can be the environment, waste heat, special heat sources, such as solar energy).

$$\eta_{reg} = \frac{l_{sp}}{l_{max}} ,$$

where l_{sp} is specific work of certain plant (design or real values), l_{max} is maximal work which can be obtained by given scheme.

The given criterion estimates a perfection of energy generation process during any type of regasification. Herewith, the values of maximal specific work are determined dependently on working fluid and thermodynamic parameters of its storage (for methane stored with pressure 0.1 MPa and temperature of 112 K values of maximal work are presented on table 1. The third criterion is relative COP which is a relation of thermal COP of designed or existing energy plant to a maximal thermal COP:

$$\bar{\eta} = \frac{\eta_{th}}{\eta_c} .$$

This criterion estimates a thermodynamic perfection of energy generation process during utilizing a cold energy of cryogenic product.

Table 1. Characteristics of the different methods of cryogenic product cold energy utilizing.

Method of cryogenic product cold energy utilizing	Maximal specific work lmax, kJ/kg	Maximal pressure of cryogenic product Pmax, MPa	Features
Utilizing a cryogenic product as a heat sink in thermodynamic cycles	1093-1146	0.1	Necessity of heat engine application
Pressurizing by pump use	853.3	65	Necessity to use pumps and turbines
Thermal compression during regasification	1258	320	Necessity to use high-pressure tanks and turbines

For energy estimation of the cryogenic product cold temperature potential utilizing it will also be useful to introduce a criterion which characterize an amount of energy which can be restored from the amount of energy consumed during cryogenic product liquefaction. Mean values of the energy consumed during LNG liquefaction are equal to 1200 kWh. The coefficient of restored energy can be calculated as:

$$k_r = \frac{N}{W_{\Sigma}} .$$

Among additional criteria there can be the values of added Q_1 and rejected Q_2 heat, maximal pressures in cycles, temperature and pressure of utilized cryogenic product, parameters of high heat source and the environment.

6. Conclusion

The analysis presented in this work is executed with the purpose to suggest general estimation methods of energy plants which utilize cold energy of cryogenic fluids. Several ways of energy generating during cryogenic product regasification was chosen for analysis and comparison: utilizing of the cold energy to reject heat from the thermodynamic cycle; increase of the cryogenic fluid pressure with its further expansion and energy generation as well as a combination of both. Calculation shows that in extreme case optimal way to utilize cold energy of cryogenic product is its thermal compression in closed volume with its further expansion. However, this process requires special fuel tanks which are capable to resist pressure with values about 320 MPa which is impossible in current level of science and technique development. In case of thermal compression to a values which corresponds with current technical possibilities, an amount of work generated after the thermal compression is almost the same as in case of mechanical compression by pump.

Utilizing of cryogenic product as a lower heat source has its own features. Provided calculation of maximal work corresponds to an extreme case with infinite number of Carnot cycles for every temperature level. Actually, current developments has up to 3 cascades [8] which causes a necessity to solve an optimization task where pressure, temperatures and working fluid composition are variables and maximal work output and minimal costs are optimization criteria.

Also, criteria allowing to estimate both thermodynamic perfection of the energy generation process as well as to compare the same type plants which operate on the same levels of temperature and pressures were suggested. Comparative analysis of the plants which utilizes different pressure and temperature levels of the high source to use a cold energy of the cryogenic product require further investigation.

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